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ARTIFICIAL RUNNING-IN OF PISTON RINGS

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ADVANCE RESTRICTED REPORT

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SUMMARY

The performance of sliding surfaces, such as piston rings, cylinders, journals, and bearings, in aircraft engines is considered with reference to the surface characteristics that they possess before and after running-in, prior to service operation. The phenomena accompanying the running-in process are analyzed. Means of eliminating the running-in process and of increasing life and performance of piston rings and bearings by artificial running-in are suggested. The aspects of running-in that are considered may, in general, be applied to sliding surfaces other than piston rings. Information on the various phases of running-in have been obtained chiefly from literature.

INTRODUCTION

The piston ring is among the foremost of engine parts that limit overhaul periods of aircraft engines (reference 1). The short life of the present-day piston ring, together with the waste inherent in the running-in of piston rings, tends to make the piston ring a costly engine component. For these reasons, it is fitting that sufficient investigation of the performance of the piston ring be conducted until the engine part yields trouble-free operation over long periods of time.

After its manufacture, a piston ring must be broken in, in order that its performance characteristics may be improved prior to service operation. Highly loaded bearing surfaces of all types, such as plain journal bearings and cylinder barrels, are also broken in.

Modern methods of breaking-in are empirical. Little attempt is made to determine how far running-in should be carried before service operation. Breaking-in of sliding surfaces usually includes operation at low speeds and loads and use of special lubricants for a period of time called the "run-in period." The breaking-in of piston rings for aircraft engines sometimes involves preliminary hand lapping. Experimental aircraft-engine cylinders may be sandpapered prior to engine operation. Despite these preliminaries, the piston ring remains the chief maintenance problem for military aircraft engines.

The advantages accruing from running-in are plentiful, albeit vaguely appreciated, but the waste associated with the running-in process is great. This waste represents loss of time, labor, and material expended on the running-in period.

It is obviously desirable to minimize or to eliminate the running-in process. Toward this end it is helpful to envision a process of artificial running-in. Artificial running-in, namely, the premanufacture of surfaces that would fit a piston ring or other slider for immediate service use, is the logical substitute for running-in.

It is the purpose of this paper, after the concept of artificial running-in is raised, to examine in detail (mainly from literature) the phenomena that constitute running-in and to suggest how these phenomena may be caused to occur on a piston ring without resort to the procedure of running-in. Such an artificially run-in piston ring or other sliding surface might be capable of being satisfactorily employed in an engine under service conditions immediately after installation in the engine. This study was conducted at the Langley Memorial Aeronautical Laboratory, Langley Field, Va., during the winter of 1942.

DEFINITIONS OF TERMS

The following terms used in this paper and in other papers have been collected for convenience of reference:

sliding of surfaces - Relative translation of bodies in contact under pressure.

breaking-in - The process of intentionally sliding new surfaces prior to operation under service conditions.

wearing-in - The phenomenon of wearing one surface against another such that more favorable performance characteristics exist after the completion of the wearing.

running-in - The wearing-in prior to service operation of the sliding surface of a machine part by operation of the machine in which the part is used.

wearing-out - The phenomenon of wearing one surface against another such that less favorable performance characteristics exist after the completion of the wearing.

load-carrying capacity - The maximum load or pressure that sliding surfaces can support without seizure or wearing-out.

performance characteristics - A general term used to designate, collectively, load-carrying capacity, friction force, wear, and temperature rise of sliding surfaces.

supersurface - That part of a solid body immediately adjacent to a surrounding fluid, a purely two-dimensional geometric concept.

surface profile - The microscopic topography of a supersurface. (See fig. 1, from reference 2, for photomicrographic examples.)

surface roughness - A rating assigned to a surface profile to represent some quality or characteristic of the profile.

percentage bearing area - The percentage of area of a plane, parallel to and at a given distance from the nominal surface, intersected by the surface profile; figure 2 illustrates the construction of a bearing-area curve from a record of the profile.

roughness number - The distance between planes of different percentage bearing area expressed in microinches.

peak roughness number - The distance between the planes of 2-percent and 25-percent bearing area, expressed in microinches; figure 3 illustrates a profile trace of low peak roughness number as determined by bearing-area curve.

rms - The root-mean-square value of a surface profile expressed in microinches; the profile may be the actual profile or the profile that is determined by a measuring instrument.

CHARACTERISTICS OF RUN-IN SURFACES

DETECTION AND MEASUREMENT

The running-in process makes itself evident in two ways:

1. It modifies the sliding surfaces of piston rings, plain journal bearings, and other sliding parts.

2. Because of this change in surface, it modifies the performance characteristics of these piston rings, plain journal bearings, and other sliding parts.

The changes made to a surface during running-in must first be detected and their extent must then be measured if they are to be reproduced by manufacturing methods.

The phenomena that indicate the difference between a virgin and a run-in piston ring may be any combination of the following:

1. Formation of Beilby layer on piston-ring face

2. Change in surface profile on piston-ring face

3. Change in shape of piston-ring face or cylinder barrel

4. Formation of new material on piston-ring face

5. Modification of radial-pressure pattern

6. Change in metallurgical structure

7. Removal of loosely held surface material

For surfaces other than those of piston rings, all of the foregoing phenomena may be present except 5; for example, a journal bearing might show all of the listed phenomena except 3 and 5.

Beilby layer. - In 1901, G. T. Beilby stated that surfaces which had been metallographically polished showed a thin layer of structure different from that of the basis metal when viewed under the microscope (reference 3). He inferred that this superstratum was similar to the Rayleigh layer which had been produced earlier on transparent solids such as quartz. The Rayleigh layer could be detected by its changed refractive index, but no means of detection of the Beilby layer was found until the 1930's when electron diffraction came into active use. Beilby had assumed that the layer which now bears his name consisted of amorphous metal although he could not be sure that it did not consist of crystals too small to be resolved under the optical microscope.

The use of X-ray diffraction had failed to reveal the presence of the layer because, as it was later found, the layer was so thin that X-rays passed through and were diffracted chiefly by the basis metal. Electrons, because of their poor penetrative power, did not pass through the layer and hence were diffracted only by the layer. Thus, electron-diffraction methods constituted a direct means of detection of the Beilby layer.

Electron-diffraction patterns may be obtained as transmission patterns with only very thin foil. Reflection patterns are the

only suitable means to be used with specimens of any considerable thickness; hence, specimens, such as piston rings or bearings, are examined only by reflection methods.

The Beilby layer is thought to be formed by the extremely quick solidification of surface metal that is melted during sliding. Local pressures during rubbing are extremely high and local temperatures reach the melting point of the sliding material (reference 4). The heat capacity of the metal surrounding these molten spots is so high, compared with the small amount of heat generated there, that solidification is instant. This short time interval during which solidification occurs is thought insufficient to allow the crystals to orient themselves as usual, resulting in an amorphous layer. Another view held by other authorities is that the Beilby layer consists of crystals so small as to yield no discernible pattern. The evidence presented by such investigators as L. H. Germer, F. Kirchner, J. T. Burwell, J. Wulff, W. Cochrane, G. I. Finch, and others on the constitution of the Beilby layer are well summarized in references 5 and 6.

The electron-diffraction patterns yielded by the Beilby layer are similar to those caused by liquids, such as mercury, at room temperature (reference 7, p. 171). The disordered array of molecules that constitute the layer has been likened to the surface of a liquid. Even as at the surface of a liquid, surface forces are high. Great energy is available for adsorption of molecules of other materials (reference 8(a)). Then too, chemical reactions may be hastened by this energy. The surface energy of the Beilby layer is so great that materials deposited on the surface by physical means assume the random orientation of the layer until a considerable thickness of deposit has been built up (reference 8(a)). On crystalline materials, however, even very thin deposits will show their normal structure. These surface forces undoubtedly act to hold fluid monolayers very tenaciously. It is thought that the fluid films formed on the Beilby layer are more resistant to removal than those on crystalline surfaces (reference 9).

The Beilby layer is known to be hard. It is held to be wear resistant because its formation is accompanied by decreased time rate of metal removal during rubbing (reference 7, p. 173), as has been made apparent by experiments on journal bearings. It has been shown that metal is removed from the bearing surfaces at a constantly decreasing rate during the running-in process. During the same period of time the Beilby layer was continuously growing. Observations of piston rings and cylinders of aircraft engines showed the existence of relatively thick layers after run-in (reference 8(a)). The depths to which these layers form on engine parts have never been exactly determined, but they are greater than those produced on hand-polished specimens. Such is the thickness of the layer on cylinders

that several rubbings with emery paper are required to remove it (reference 8(a)). Hand polishing yields layers from 30 to 50 A in thickness as determined by controlled etching (reference 8(b)). Controlled etching consists in removing known amounts of surface material from a specimen. From the dimensions of the specimen and from the amount of material removed from the specimen, the thickness of the surface layer removed may be calculated. The process of alternate etching and photography of electron-diffraction patterns continues until the characteristic pattern of the Beilby layer is no longer obtained. The sum of the thicknesses of all layers removed by etching is the thickness of the Beilby layer.

Surface profile. - It is current practice in America to express surface roughness as rms (reference 10). This designation is many times meaningless, especially when the methods of production of the profiles are not specified. For instance, a lapped surface and a ground surface of equal rms may have far different operating characteristics and over-all profile heights. A self-explanatory diagram of common profile differences is given in figure 4, from reference 11. In general, a lapped surface consists of a supersurface that is essentially smooth although pied with pits. A ground surface consists of equal peaks and valleys. Practically all machined surfaces can be classified as one or the other type. The difference between the two types of surface manifests itself as a low peak roughness number for surfaces without protuberances and as a high peak roughness number for hilly surfaces.

Regardless of what the initial profile may be, the peak roughness number decreases during the running-in process, except for extremely smooth surfaces. The action consists, as determined microscopically, in removing the tips of peaks and thus converting them to plateaus. That peaks are converted to plateaus has been shown by the taper-section method of examination. If the oil-film thickness between sliding surfaces is construed to indicate the distance between definite percentage bearing areas of some value less than 25 percent on each surface profile, it is then seen that a low peak roughness number will indicate a small distance of projection of profile peaks into the film.

Pits are needed on smooth surfaces to prevent the oil from wiping off as a sheet. Two independent theories adequately explain this phenomenon (references 12 and 13). It must be remembered that the presence of pits need not influence the surface topography of the plateaus of the surface profile. That is, pits may exist in surfaces of both high and low peak roughness number. The trend in topography of surface plateaus is toward smoothness. This tendency is shown in a number of cases.

More metal is removed from rough surfaces than from smooth surfaces during the running-in process. The amount of metal removed is proportional to the surface finish, as shown by figure 5 taken from reference 14(a). Hence, rough surfaces contribute much to abrasive wear by filling the lubricant with wear metal.

Worms and worm gears develop greater load-carrying capacity and greater efficiency after running-in as the initial surface finish is made finer (reference 14(b)).

It is believed that the formation of a profile of low peak roughness number would aid in maintaining a monomolecular film under boundary-lubrication conditions by increasing the number of long-chain molecules standing on end atop the extremities of the super-surface.

Fatigue resistance of smooth surfaces is greater than that of rough surfaces. It seems logical that the corrosion resistance of a smooth surface should be greater than that of a rough surface inasmuch as a rough surface presents greater profile areas for attack. Also, corrosion fatigue, as with all fatigue phenomena, is more deleterious to rough surfaces than to smooth surfaces.

The direction of sliding of surfaces is indicated by scratches or grooves parallel to the direction of sliding if contact occurs. Records of a sliding surface made with tracer instruments show deep, closely spaced pits and peaks, if taken orthogonal to the direction of sliding, and less closely spaced, if taken in the direction of sliding (figs. 6(a) and 6(b), from reference 15). These marks are more or less irregular depending on the method of surface finish and the amount of abrasive present in the lubricant. Whether these crevices serve as oil ways to distribute oil over the surface or whether they serve as channels for escape of the lubricant under pressure between the sliders has never been clearly determined. These scratches are sometimes termed "run-in marks."

The most common means of measuring surface roughness as rms is by use of either the Brush surface analyzer or the Profilometer. At present, the only common nondestructive attempt at recording the actual shape of the profile is by means of the Brush surface analyzer. For surfaces less rough than 250 microinches rms, the rms determined by the instrument is different from the true rms as determined microscopically by taper sectioning. For ground surfaces in the order of 1 microinch rms as measured by the instrument, the true rms is about 10 microinches rms (reference 14(c)). Such instruments serve usefully in production inspection and in some research but they fall short of yielding precise research data.

Taper sectioning is a very exact method of viewing surface profiles but it requires the destruction of the specimen. Evidently, destructive testing must be avoided if a series of tests is to be run on a specimen, such as a piston ring, where surface profile is under study.

It must be noted that the surface roughness of the face of a piston ring varies around the circumference of the ring after run-in. The NACA has made investigation of this relation between radial-pressure pattern and circumferential variation of surface roughness. Aircraft-engine piston rings had been lapped in cylinders before test in order to eliminate the variable of initial surface finish in accelerated high-output test runs. The surface finish of these rings was evaluated by means of a Brush surface analyzer equipped with both rms meter and oscillograph. Roughness measurements were taken at three points on the ring face, namely, adjacent to the gap, opposite the gap, and at a point halfway between the two, which was called the 90° point. Both circumferential and axial roughnesses were determined.

It was found that, after lapping, the finish was roughest at the 90° point, with roughnesses at the other two stations approximately equal to each other although slightly lower at the gap. This roughness pattern was similar in both directions of travel.

When the rings were examined after accelerated high-output tests that had not severely marred the surfaces by scuffing or scoring, the original shape of roughness pattern was found. It was shown that at all points on the ring the following expression held:

$$\frac{\text{log rms after running}}{\text{log rms after lapping}} = \text{constant}$$

The rings in question possessed high plus circularity. The radial-pressure pattern of such rings taken around the circumference is similar to the finish pattern, that is, smooth at gap and 180° point, and rougher between. Because the rings grew smoother with rubbing it followed that points of the highest radial pressure gave the most wear during lapping and gave the smoothest surfaces. Indeed, it would seem that, if a piston ring were lapped in a cylinder and the resulting surface-finish pattern were determined, the radial-pressure pattern would follow.

Shape change. - The hydrodynamic theory of lubrication states that, if sliding surfaces converge to form a correctly proportioned wedge-shaped space, the optimum conditions for wearless operation are established. Journals in bearings automatically follow this criterion by displacing themselves eccentrically. Approximately

one fourth of the total bearing is available for supporting the load. The Michell-Kingsbury-Nomy types of bearings make use of pivoted slippers to establish the wedge-shaped oil film and increase the length of circumference that can carry load (reference 16). Applied to journal bearings, pivoted shoes have enabled unit bearing pressures to be tripled without excessive bearing wear.

Piston rings are assembled in piston grooves with appreciable clearance in order to minimize ring sticking. This clearance, as well as the clearance of the piston in the cylinder, permits the piston ring to rock with respect to the cylinder. Rocking brings the cylinder wall into contact with the edges of the piston-ring face where wear takes place. The continuous wearing of the ring edge against the wall causes the ring face to become convex. Inspection by the authors has shown that high-output aircraft-engine piston rings presented a continuously curved convex face shape after operation. This shape agrees with hydrodynamic theory that postulates a biconical face shape as optimum (reference 17). The percentage of the stroke over which full fluid lubrication occurs increases as the optimum face shape is approached.

The effect of gas pressure on ring wear during operation is in dispute. One authority states that gas pressure has little effect on ring wear (reference 18). The smallness of the effect is thought to be due to the high potential separating force of the fluid film that is built up by the time maximum gas pressure can develop behind the piston rings through the small piston and cylinder clearances. Other sources show that gas pressures do influence piston-ring wear, especially when unit wall pressures are low (reference 19).

Because the fluid film is in every case very thin, the degree of taper of a biconical ring face need be only slightly greater than the maximum angle that the ring can make with the cylinder center line under extreme rocking conditions. Because the amount of rocking is variable over the stroke, the angle produced by the planes of ring and cylinder wall must be variable. The only practicable means of obtaining this variable angle is for the ring to have a continuously curved convex, not biconical, face.

Local thermal distortions produced by temperature change of the operating mechanism will cause the surface of the slider to depart from its nominal shape (reference 20). During running-in the slider tends to remove these protuberances where they exist.

New materials on surface. - The surface of a slider may undergo reaction with the lubricant to form surface compounds. The action of chemical polishing agents and, in part, the action of oiliness agents are attributed directly to the formation of surface compounds.

Even cutting fluids used in machining operations depend to some extent for their action on the organometallic compounds of varied frictional coefficients that are formed on the work surface.

Chalmers and Quarrell (reference 21, pp. 232-233) state that the high wear of engine cylinders by aluminum pistons is caused by aluminum trioxide, sapphire. This oxide becomes amorphous during running and recrystallizes on stopping to form sapphire, which abrades steel readily. After the engine is started, some time elapses before the amorphous structure returns. The amorphous form of the oxide does not wear the cylinder badly. Aluminum-magnesium-alloy pistons, which always form amorphous oxides, might yield reduced wear. This idea is under investigation according to the authors of reference 21.

Surface compounds may be detected by chemical methods and by such means as electron diffraction, X-ray diffraction, and others.

Another change in surface composition occurs when cast iron is a slider. Cast iron when rubbed has the property of bringing occluded graphite to the surface. This graphite forms a layer oriented in the direction of sliding (reference 8(a)). It is claimed by some authorities that, when this graphite is removed, wear becomes great and unpredictable. Graphite is believed to be more easily oil-film forming than metals.

<u>Change in pressure pattern of ring.</u> - The NACA has found that, in accelerated high-output tests, piston rings maintain the original radial-pressure pattern after operation provided that no ring failure has occurred. Ring failures, either of the type where gas blow-by has increased or where scuffing has occurred, modify the ring pattern. The NACA has found that increased temperature of a piston ring in a cylinder decreased the diametral tension of the ring. From these results, it can be reasoned that high local temperatures, such as those caused by blow-by or scuffing, will lower the corresponding local radial pressures so as to warp the pressure pattern of the ring. Illustrations of such modifications are not uncommon in piston-ring literature (reference 22).

<u>Metallurgical change.</u> - Sliding of surfaces is many times accompanied by cold work, always so when contact between the surfaces occurs. It has been observed that working by any of a number of means including sliding will reduce the grain size of metal and also deform the grains to produce oriented structure (reference 8(c)).

Cold-working also affects the affinity of the lubricant monolayer for the metal, either directly by modifying attractive surface

forces or indirectly by preferentially attracting foreign materials (reference 12). Worked surfaces are prone to corrode, however, because internal stresses lower the corrosion resistance and the corrosion-fatigue resistance (reference 7, p. 172).

Many materials gain in hardness and wear resistance directly because of metallurgical phase changes effected by cold work. Hadfield manganese steel, for instance, is a common material that attains its complement of abrasion-resisting qualities directly by cold work.

Removal of loosely held surface material. - The advent of superfinish has focused attention on loose metal "fuzz" present on newly machined surfaces. This metal, normally, is quickly worn off during operation and finds its way into the lubricant. Minute particles of loose abrasive are also present in the outer surfaces of machined parts that have been finished by conventional abrasive means. The exponents of superfinish claim that neither loose fuzz nor abrasive is present on superfinished surfaces (reference 14(d)).

Miscellaneous. - J. T. Burwell and H. W. Fox in unpublished research conducted at M.I.T. found that for journal bearings the time rate of metal removal is about the same as the time rate of change of friction torque and time rate of change of lubricant temperature. It would seem that wear is a good criterion of performance characteristics of sliding surfaces. Hence, the running-in process was defined in this paper on the basis of slider wear.

If a bearing is run in at some definite operating temperature and if sometime thereafter the operating temperature is increased, the bearing passes through another run-in process. The increase in temperature is characterized by decreased seizure load, increased friction, and increase at the point of minimum friction in the variable $\frac{4r^2ZN}{c^2p}$

where

r radius, inches

c diametral clearance, inches

Z absolute viscosity, centipoises

N angular velocity, rpm

p unit pressure, pounds per square inch

After the sliding surface has been run in at the increased temperature, the performance characteristics will have approached post run-in values because of the lowered oil viscosity that permits the surfaces to approach each other and thus to wear off more of the surface profiles (reference 14(e)). It has been shown also that oils of light viscosity run in surfaces smoother than heavier oils of the same stock. Actual operating viscosity has no effect on the phenomenon. When both oils are heated to the same viscosity, the heavier oil still wears the surface rougher (reference 14(f)).

Running-in increases the load capacity of sliding surfaces, as shown graphically in figure 7, from reference 14(e). It will be noted that higher loads may be carried by a run-in surface, without destroying thick film lubrication, than by a virgin surface. Because the condition of thin film lubrication connotes higher wear than does hydrodynamic lubrication, it is seen that the wear decreases as the surfaces are run in. Figure 7 shows directly that friction torque is less for a run-in surface.

Another means of showing the load-carrying advantages of running-in is by the constant-torque friction-load curve for a plain journal bearing. (See fig. 8 and reference 23.) Because friction torque is proportional to the product of the coefficient of friction and the normal load,

$$T = kfp$$

where

T friction torque

f friction coefficient

p load

k proportionality constant

With torque constant,

$$pf = K$$

where K is a constant. This expression is the equation of the hyperbola shown in figure 8, from reference 23. Because running-in lowers the friction and because smooth surfaces have less friction than rough surfaces (fig. 9 from reference 14(a)), the shapes of the curves in figure 8 are apparent. The curves in figure 8 show also that a greater change in load-carrying capacity is produced by running in the smooth surface than by running in the rough surface for

the same period of time under constant torque. For the same period of time of running-in, however, the rough surface cannot achieve the same load capacity as the smooth surface. This difference in load capacity indicates that the fundamental idea of roughening surfaces in order that they may run in more quickly is fallacious. It would appear that the running-in process is never completed, for a bearing may continue to improve continuously in performance during operation. (See fig. 10, from reference 14(e).)

CHARACTERISTICS OF RUN-IN SURFACES

ARTIFICIAL PRODUCTION

To some extent each of the characteristics of run-in surfaces may be artificially produced, that is, be produced on the piston ring without resort to running in the ring in an engine.

Beilby layer. - It is possible to produce the Beilby layer on surfaces such as cylinders without running in the cylinder in an actual engine. Rubbing under properly controlled conditions will produce it. In order that the surface will not wear out before the layer is formed, rubbing loads must not be too high nor sliding speeds too great. In order to form the layer at all, however, rubbing loads must not be too low nor sliding too slow. Pure hydrostatic pressure will not produce the layer. Shearing stress must be present (reference 8(d)). In general, the Beilby layer cannot be formed on metal surfaces that are rubbed by metals of lower melting point (reference 7, p. 173).

Deposition of certain coatings by methods, such as cathodic sputtering, flashing, electrolysis, and oxidation, may yield amorphous films.

The effect of adsorption of lubricant and combustion gases in the engine may cause the natural layer to differ from the artificial (reference 8(e)). For example, bearings run under an oxygen blanket show increasingly high seizure loads as the rate of oxidation increases (reference 14(e)). Rouge, when used for polishing, has a tendency to give off oxygen to metals (reference 8(e)); thus, surfaces polished with rouge might conceivably be more seizure resistant than those polished with inert agents.

Surface profile. - Means of producing smooth surfaces and surfaces of low peak roughness number are available by mechanical, chemical, and electrolytic methods (reference 21, pp. 265-267). Lapping and superfinishing yield the smooth surfaces. The finish may be made smoother by prolonging the machining operation or by electropolishing (reference 14(d)). Machine polishing removes high peaks

by flowing the metal, but the action is usually so drastic that much of the flowed metal is worn off during the initial moments of operation under service loads.

When certain additives known as chemical polishing agents are placed in lubricating oil, they react with the metal sliding surfaces to form compounds that have low wear resistance, low shear strength, or low melting points (reference 14(g)). Because the reaction proceeds only with unattacked material, the peaks alone will be worn down because they are being constantly abraded and exposed to the additives. Certain of these additives, such as tricresyl phosphate, are temperature selective; that is, the reaction decelerates as the local temperature drops (reference 14(g)). Temperature-selective additives need never be removed from the lubricant; when they have performed their function of flattening surface peaks, they become inoperative. Other additives that are not temperature selective must be removed from the lubricant after their purpose has been fulfilled in order to prevent excessive wear during service. A profile consisting of very flat peaks may be obtained in this way. When both oiliness agents and chemical polishing agents are added to lubricants, the wear resistance of the surface after running-in is increased manyfold (reference 14(g)).

Electropolishing (electrolytic brightening) can produce very smooth surfaces that are markedly free from asperities. This method may be used to remove scratches from superfinished surfaces (reference 14(d)). Whether such smooth surfaces are suitable for operation as sliders is determined by the abrasive content of the lubricant. If the lubricant is relatively free from abrasives, such a surface will retain its smoothness during service (reference 14(d)); if not, the surface will roughen.

A surface consisting of plateaus surrounded by deep gorges can be produced by a process essentially the same as electropolishing. One such process has been patented and is used to produce this type of surface on chromium plating. As with electropolishing, the work surface serves as the anode and current is flowed through an electrolytic solution. In general, if the electrolyte is such that current can more easily flow through the metal than through the electrolyte, electropolishing will take place and the surface will become smoother (reference 21, p. 265). Under other conditions, however, certain phases of the material are selected for removal (reference 14(h)). In such cases essentially flat plateaus surrounded by gorges will result. The process is used commercially on chromium-plated sliding surfaces. Superposing alternating current on the direct electrolytic current results in deposits almost free from internal stress.

In line with the theory that run-in marks are beneficial for sliding surfaces, some engine cylinders have been machined with tool marks parallel to the axis. Draw polishing (burnishing) was one of the first means used to produce the effect. This process, however, causes the metal to flow in such manner that areas of the surface metal are weakened and break off easily under sliding; also, peaks may be flowed so that they are bent and cover over the initial surface rugosities. When this covering is detached, the original surface is exposed. Present-day means of achieving this type of finish are by use of honing without rotation, which is also called codirectional honing or functional finishing. Some authorities claim that such finish reduces initial wear (reference 14(i)).

Shape change. - It is entirely practicable to machine piston rings to a continuously curved convex face shape. Conventional machining methods such as grinding will produce the desired effect although the small amount of curvature desired indicates that precision machining may be required for this work.

The elimination of local thermal distortions may be accomplished by designing engine parts in such manner that they take correct nominal shape when heated to operating temperature.

New materials on surface. - If materials that improve the performance characteristics of a piston ring form on the piston-ring surface owing to chemical reaction, it would seem entirely practicable to carry through these reactions prior to engine operation. Present piston-ring coatings may actually serve the same purpose as the products of these reactions.

Piston-ring coatings are employed in order that rings may pass through the running-in process without permanent marking or wearing-out. They may also lower frictional force (reference 14(j)). Such coatings serve as buffer layers, which themselves do not wear the cylinder greatly. As the coatings wear off, the asperities of the piston-ring basis metal are permitted to come gradually into contact with the cylinder wall in order that wearing-in may occur. The coating ought preferably to be oil retentive.

Occluded graphite may be brought to the surface of cast-iron sliders by polishing operations. Colloidal graphite added to the lubricant has been recommended to replenish this graphite layer. Colloidal graphite is even better in this respect than graphite deposited from suspension (reference 8(a)).

Change in pressure pattern of ring. - Inasmuch as the only changes in pressure pattern of piston rings found to this date after

a running-in process had been completed were those caused by incipient or complete failure, it would appear that present pressure patterns should not be altered.

Metallurgical change. - Any number of methods may be used to cold-work the surface of a slider. For instance, the practice of sandpapering engine cylinders before running-in yields a cold-worked layer. It has been shown by X-ray diffraction methods that coarse abrasive yields a lesser depth of cold work than fine abrasive (reference 24).

Removal of loosely held surface material. - The most direct method of obtaining a surface free from loose metal fuzz would appear to be electropolishing. Because superfinishing has been proved to yield negligible amounts of abrasive on a superfinished surface, it can be used as a finish-machining operation where little loosely held surface material is desired.

RECOMMENDATIONS

The following tests are recommended for investigation in order to direct future development along lines that would eliminate running-in and allow a sliding surface to be put into service at the peak of its performance characteristics:

Tests to determine the effect on wear in service of piston rings and cylinders of:

(A) Premanufacture of surface profiles produced by

1. Superfinishing
2. Lapping
3. Grinding
4. Electrolytic polishing
5. Electrolytic roughening
6. Sliding on lubricant containing
   (a) chemical polishing agents
   (b) chemical polishing plus oiliness agents

(B) Premanufacture of Beilby layer produced by

1. Mechanical polishing
2. Deposition

(C) Use of rings of convex face shape

(D) Premanufacture of running-in marks

(E) Colloidal graphite as lubricant for cast-iron sliders

(F) Design of cylinder shape to produce true nominal shape under temperature conditions approximating those in service

(G) Cold-worked rubbing surfaces

ADVANTAGES OF ARTIFICIAL RUNNING-IN

Advantages anticipated as accruing from artificial running-in of piston-ring and bearing surfaces before service operation are as follows:

1. High loads may immediately be placed on sliding surfaces.

2. The lubricant is not filled with the large amount of metal worn off during the running-in process.

3. Time, labor, and money expended to run in engine parts are saved.

4. High outputs and high mechanical efficiency may be obtained and maintained by reducing friction and wear.

5. Operating life may be increased by decreasing wear.

6. Time between overhauls may be decreased because of greater dependability of parts.

7. Operating safety is increased by minimizing failures through wear, corrosion, fatigue, and corrosion fatigue.

8. Design, service, and maintenance are simplified by assuring small rate of change of dimension of sliding surfaces.

9. Design and power-weight ratio may be bettered by assuring maximum efficiency for all operating parts.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
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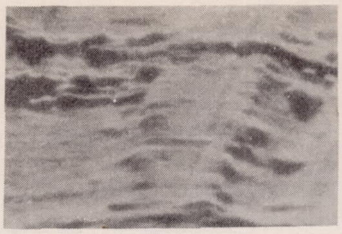
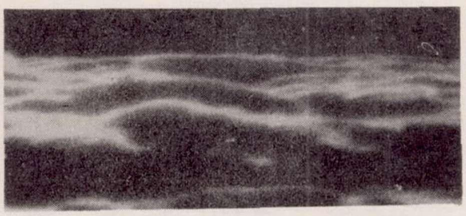


(a) Magnified 6400:1.



(b) Magnified 8600:1.

Figure 1. - Oblique photomicrographs of finish ground surfaces of steel, made with electron microscope. (Plate 2 from reference 2.)

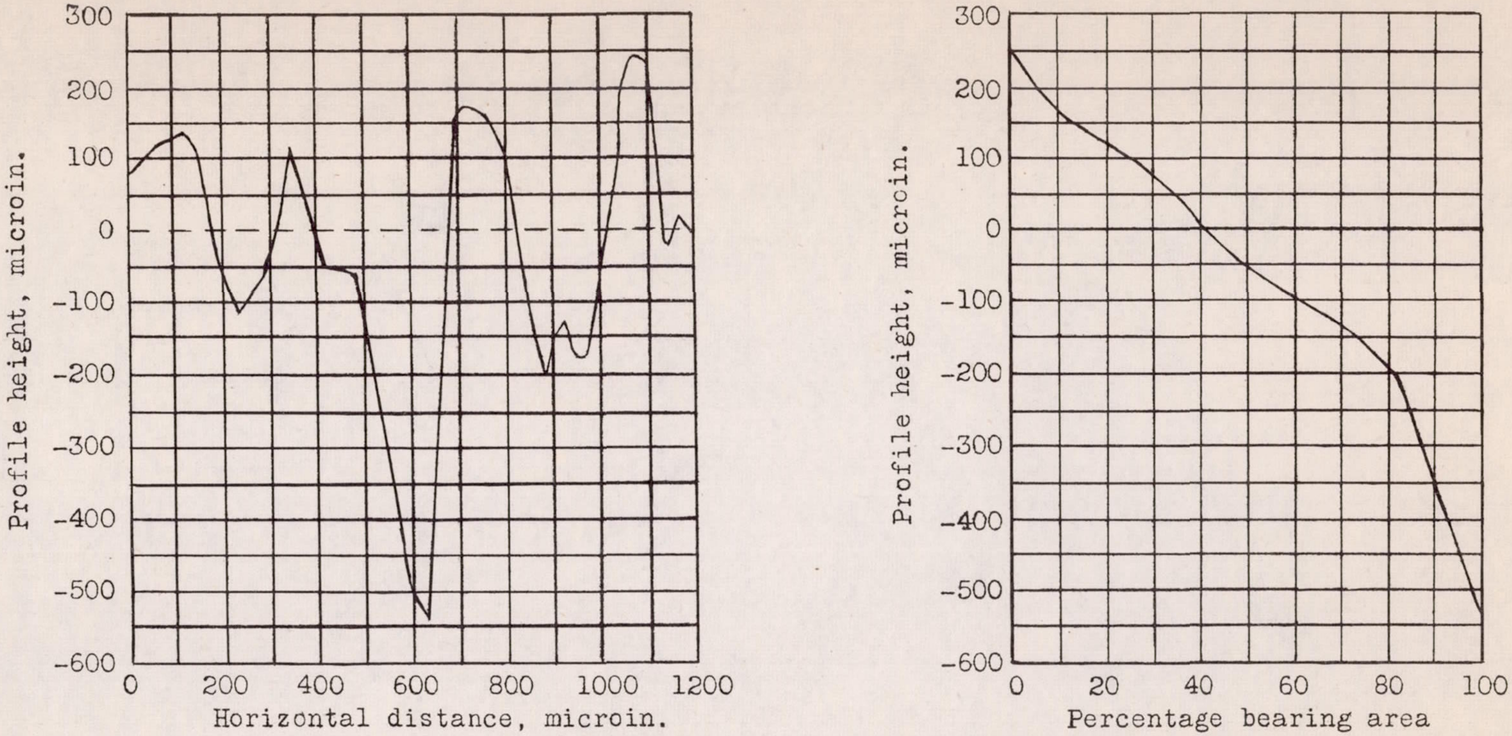


Figure 2.- Typical percentage bearing-area curve.

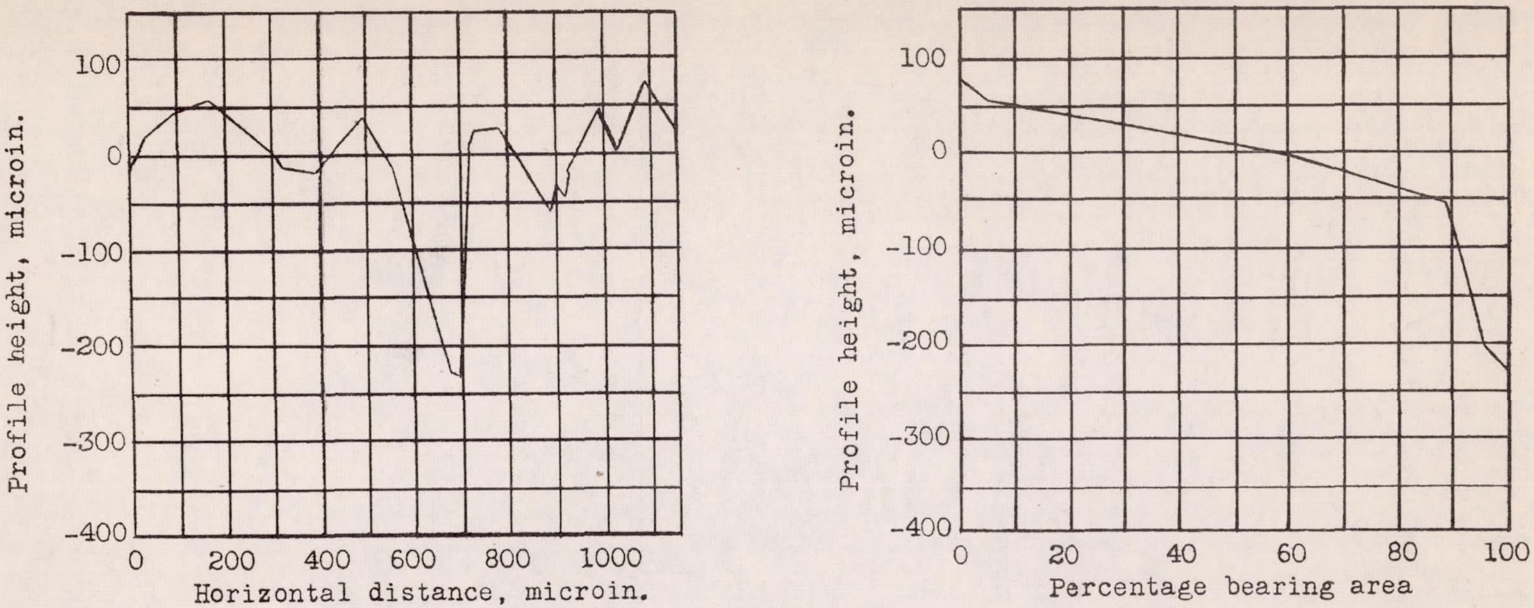
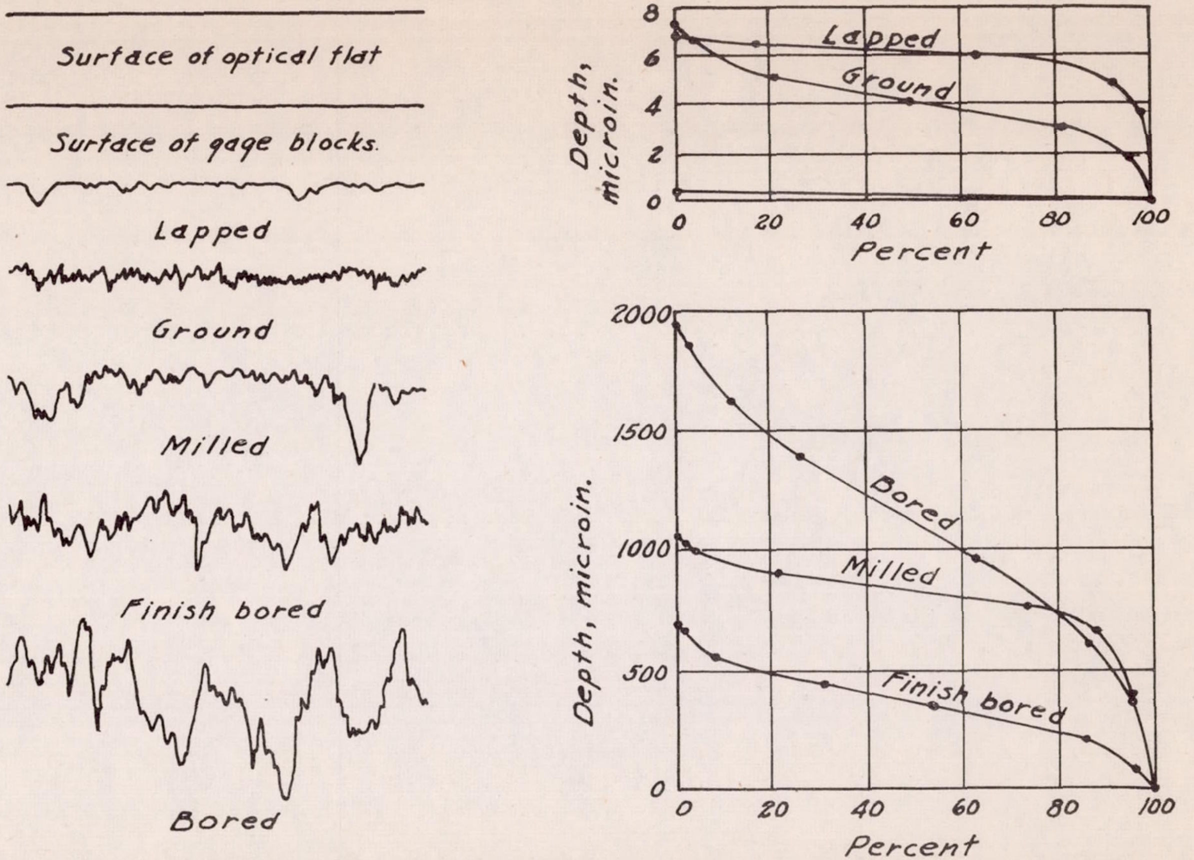
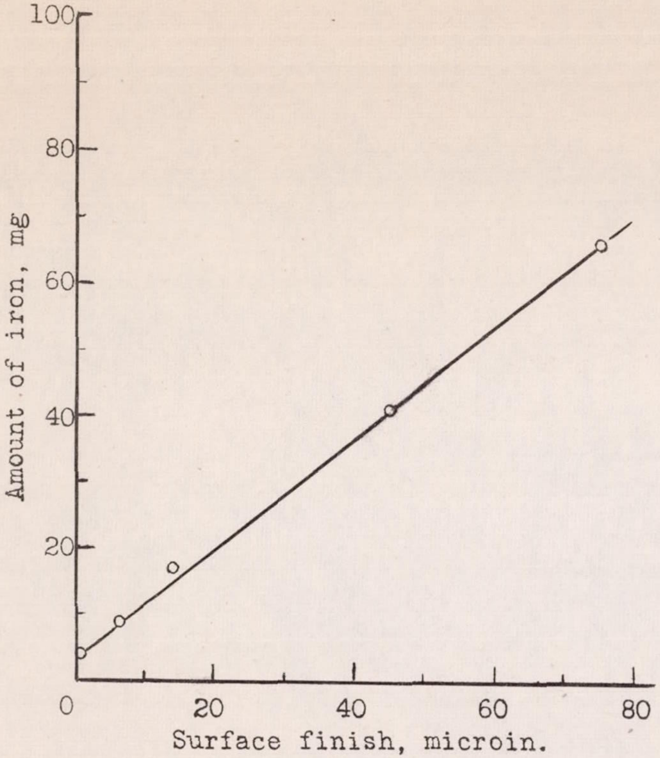


Figure 3.- Typical profile of low peak roughness number.

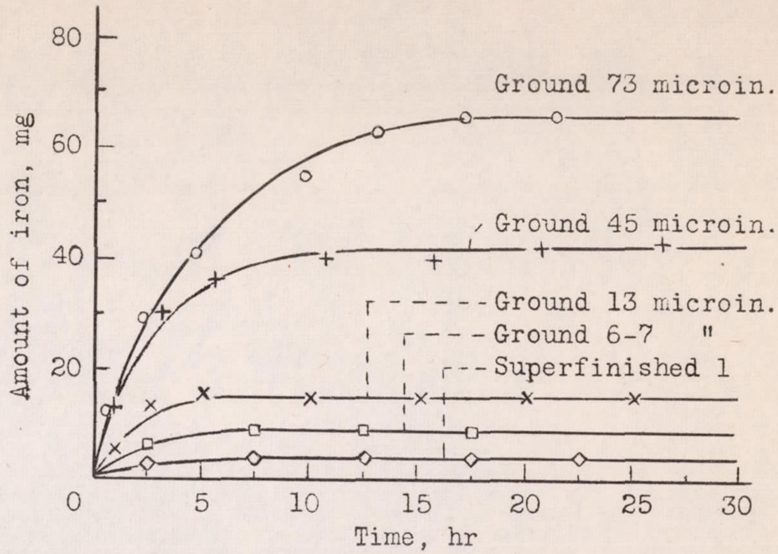


(a) Profile records. (b) Percentage bearing-area curves.

Figure 4. - Typical machined surface finishes (fig. 120/1 from reference 11).

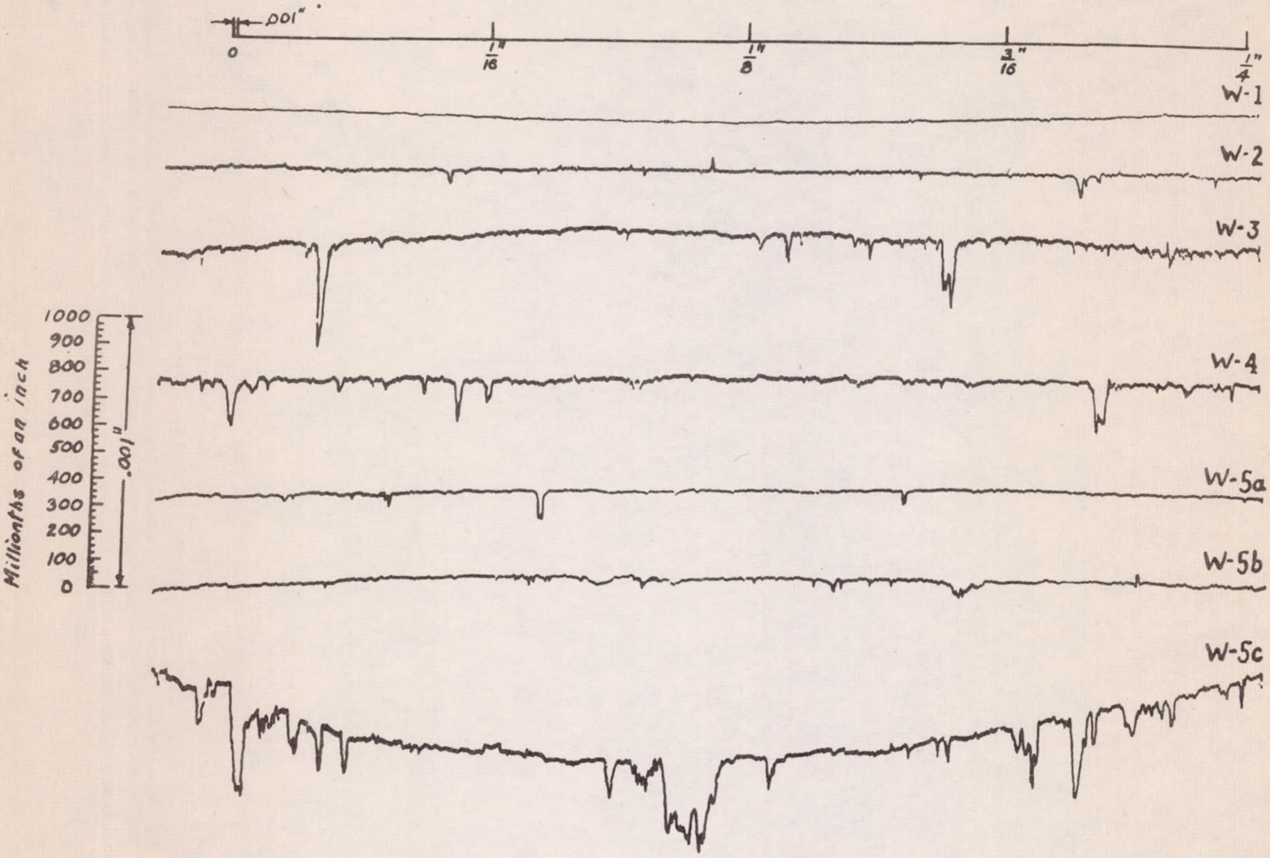


(a) Total metal removed from steel journals plotted against their surface roughness. (Figure 2 from reference 14(a).)



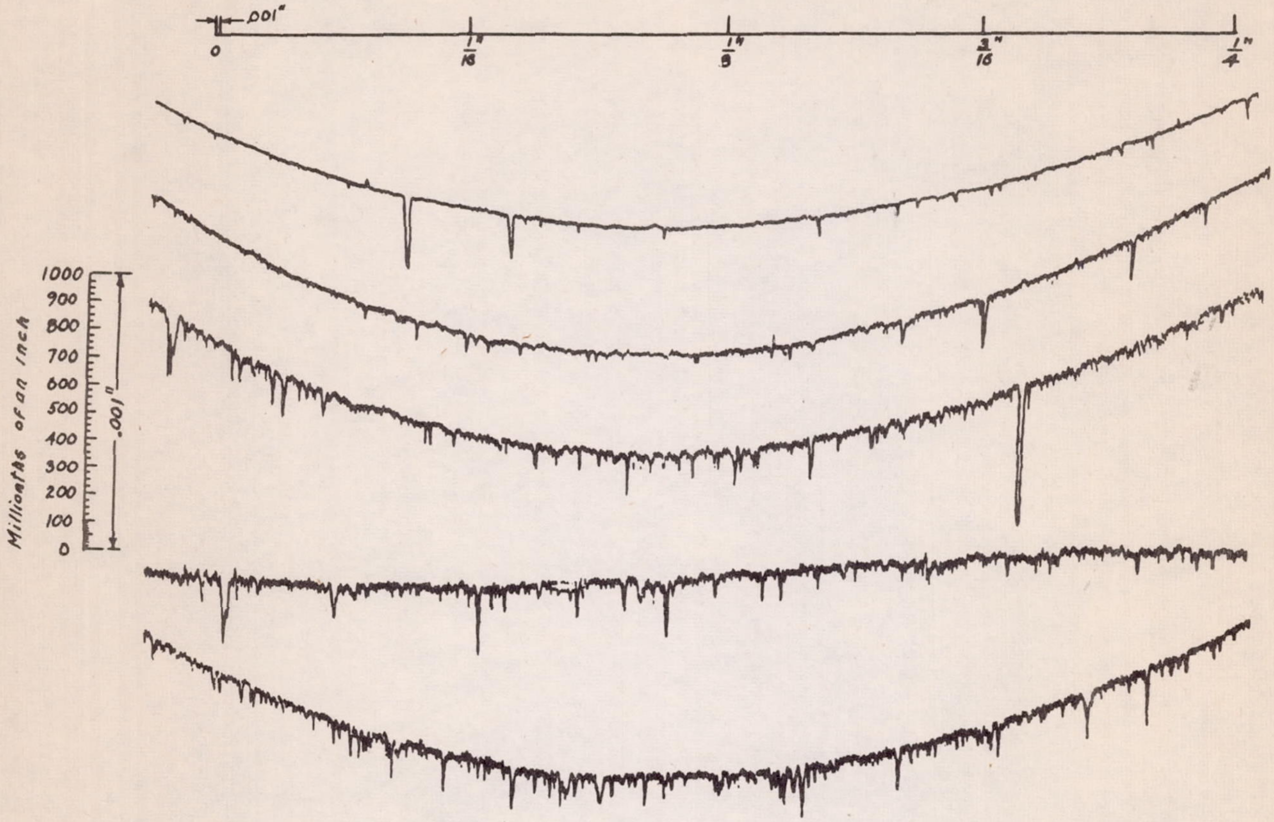
(b) Rate of metal removal from steel journals with different surface finishes running against babbitt during running-in process. (Figure 1 from reference 14(a).)

Figure 5.- Effect of surface finish on amount and rate of metal removed from steel journals.



(a) Records taken parallel to sliding. Magnification: vertical X2000, horizontal X30. (Fig. 4 from reference 15)

Figure 6. - Records of worn cylinders taken from cars after several thousand miles of operation.



(b) Same specimens as figure 6 (a) except that records were taken orthogonal to direction of sliding. Magnification: vertical X1400, horizontal X21. (Fig. 5 from reference 15)

Figure 6. - Records of worn cylinders taken from cars after several thousand miles of operation.

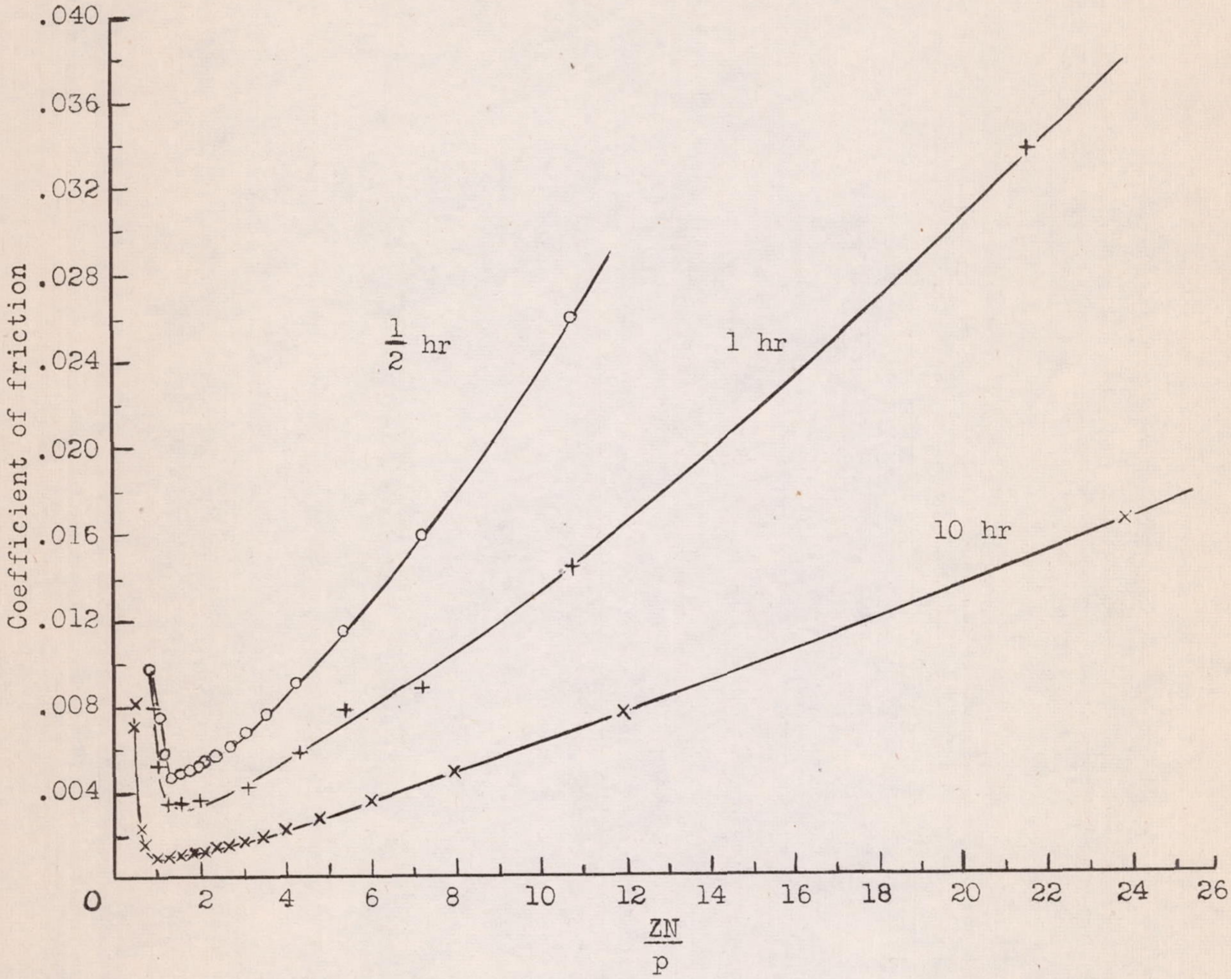


Figure 7.- Variation of coefficient of friction with the variable ZN/p as running-in proceeds (figure 11 from reference 14(e)).

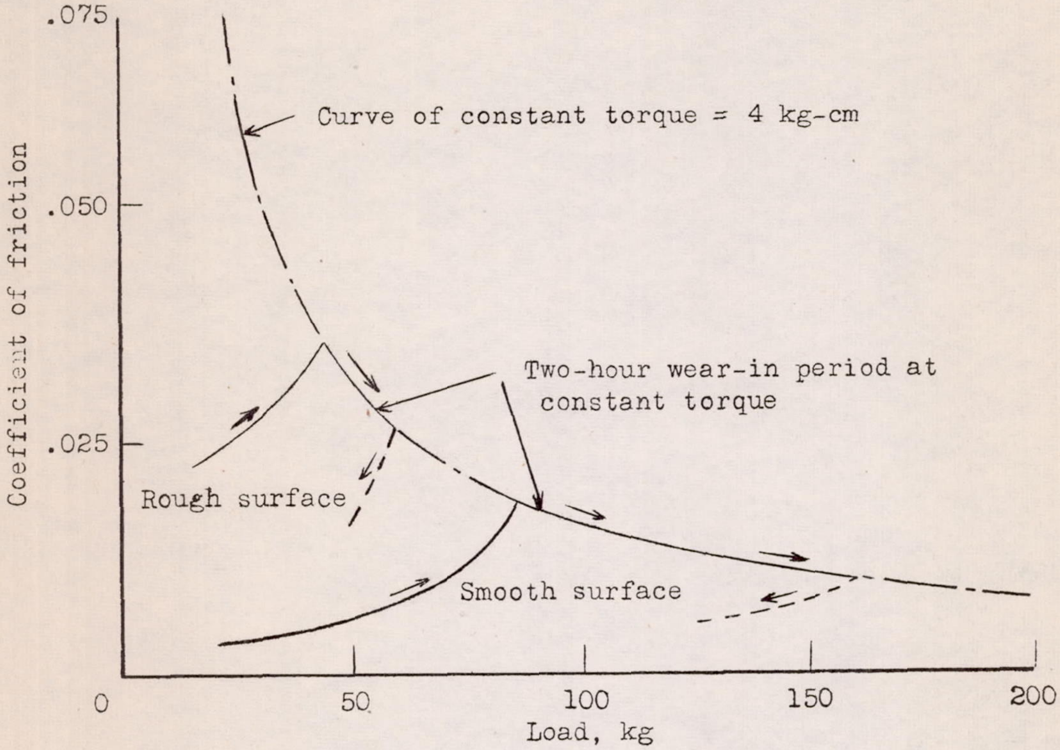


Figure 8.- Friction-load curve at constant torque (figure 24 from reference 24).

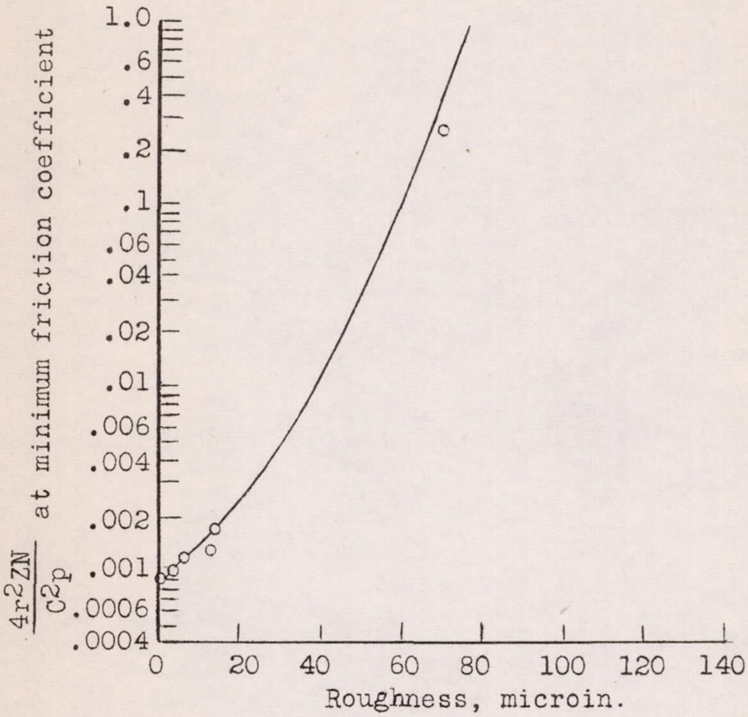


Figure 9.- Variation of Sommerfeld variable with surface roughness (figure 4 from reference 14(a)).

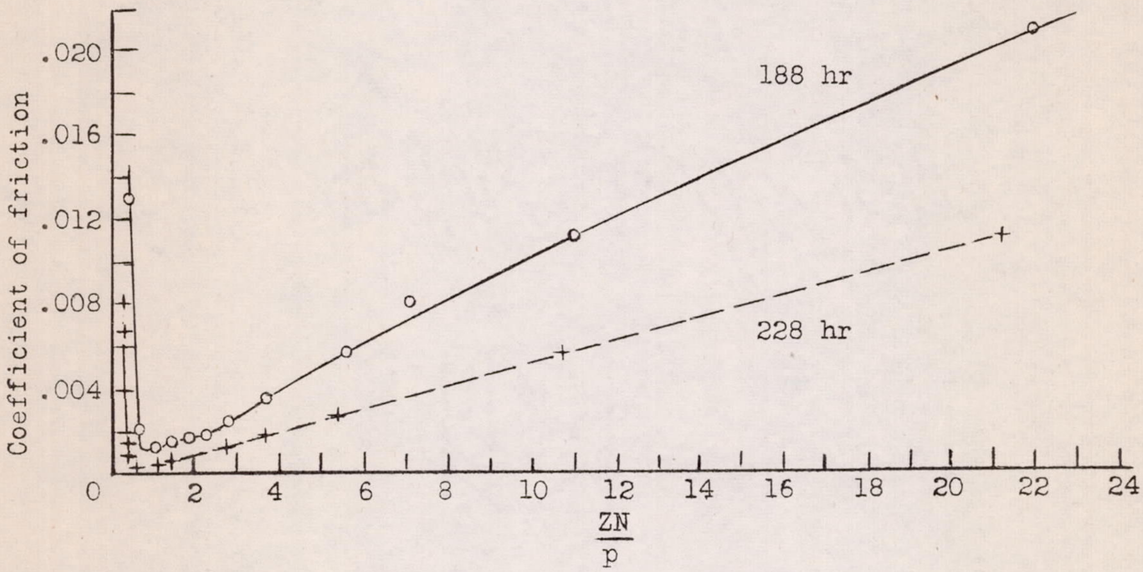


Figure 10.- Variation of coefficient of friction with the variable ZN/p as running-in proceeds (figure 12 from reference 14(e)).